THE POTENTIAL OF ADDITIVE MANUFACTURING TO TRANSFORM THE WAY SPARE PARTS REACH THE VESSELS AT THE PORTS

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ABSTRACT: It is common knowledge that ships relay for certain maintenance works while at port. They also receive the needed spare parts at / or near the port. That is why there are many workshops and spare part warehouses near the ports. The availability of parts to respond quickly to demand make inventory necessary, otherwise there are consequences, such as customer dissatisfaction, from the provider side, or financial consequences from assets downtime. Keeping spare part inventory incurs costs (mainly in capital, and in some cases in available space). Synchronous digital production technologies, such as additive manufacturing, are disturbing the established supply chains, by offering an alternative, new flexible and distributed manufacturing located closer to the end users. This paper presents the potential of additive manufacturing to transform warehouses, and workshops near the ports, due to the repositioning of industry in new business models for product design, manufacturing, distribution and service.

INTRODUCTION

The conversion of information into a digital format makes it easier to preserve, access, and share it (digitization), moving industry and manufacturing to data-driven, leading in new business models for product design, manufacturing, distribution and service. The digital form of products, in combination with technologies that allow distributed localize production, are changing the supply chain.

Additive manufacturing (AM) is an innovative technology already implemented in various sectors leading to changes not only in manufacturing, but also in the supply chain. The new technology eliminates, stages of production (e.g. assembly) and thus simplify production line. The place of production moves closer to demand. The sale is made before the production of the product, upsetting the known production and product distribution process.

Among the products that can be realized and distributed over the internet in digital form and can be manufactured locally by new technologies including AM are spare parts.

Li, et al. (2017) apply note that the existing studies indicate that AM can have tremendous implications for a spare parts supply chain since AM, due to its unique characteristics, creates the opportunity to manufacture spare parts on demand and to reduce the number of stages in the supply chain. Khajavi, Partanen, and Holmström (2014), have specifically paid attention to the spare parts supply chain and investigated the use of AM technology in such a context.

The published work regarding the observations from the actual implementation of additive manufacturing, as it is finding its way into mainstream manufacturing industry, reveals its benefits and challenges.

Since spare parts supply chain plays an important role in keeping the maritime assets running, it may gain from the introduction of AM into spare part supply chain, by having the right spare in the place and the time where it is needed, minimizing inventory and reducing delays and costs. Maritime assets are capital intensive and downtime has financial consequences, everything that contributes to functional machinery, helps in this direction.

Additive manufacturing (AM) brings new opportunities and benefits to the SPSC, but most of the studies come from the aerospace/aviation and defense. This raises the question: *What is the potential of additive manufacturing improvements to transform the way spare parts reach the vessels at the ports?*

The paper after stating the aim, gives a brief explanation of the available AM technology. Then presents the literature on the impact of the technology on the supply chain and the transportation of products and in particular for spare parts. In order to research the suitability of AM to the maritime and the factors influencing the application of AM in its SPSC, lessons can be gained from reviewing the relevant literature, especially the work on industries with moving assets, such as aerospace, and defence. The more important maritime characteristics that one must have in mind when is thinking in introducing AM in maritime are summarized. The idea to transform warehouses, and workshops near the ports into hubs is presented. Next the benefits of the digital transformation of the SPSC by the introduction of AM will be pointed out, but also barriers to overcome, and the factors for the successful establishment of this new technology.

THE AVAILABLE TECHNOLOGY

AM is based in the principle of the construction in layers by directly converting the 3D data into physical objects. Additive manufacturing is the official industry standard term (ASTM F2792) for all applications of the technology. It the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. ISO/ASTM 52900:2015c defines 3D printing as a term "often used in a non-technical context synonymously with additive manufacturing." The two terms are often used interchangeably, but there is a distinction between them: it is suggested to use the term 3d printing for low-end quality and price machines and additive manufacturing in the industrial context. Both definitions have been standardized officially according to ISO/ASTM 52900:2015 – "3D printing is the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology. The machine used for 3D printing is a 3D printer. Additive Manufacturing (AM) is the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. AM machine is a section of the additive manufacturing system including hardware, machine control software, required set-up software and peripheral

[c] ISO/ASTM 52900:2015(en), Additive manufacturing — General principles — Terminology. (n.d.). Retrieved October 19, 2019, from **https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en**

accessories necessary to complete a build cycle for producing parts."

IMPACT OF ADDITIVE MANUFACTURING ON PRODUCTION, SUPPLY CHAIN AND TRANSPORT

Market surveys predict that the introduction AM will have a major impact on industries and manufacturing (Weller, Kleer, and Piller 2015). The new technology eliminated stages of production (e.g. assembly) and thus simplify production line. The place of production moves closer to demand. The sale is made before the production of the product, upsetting the known production process.

The production facilities can now be located closer to the customer in Europe or North America, where it is more direct response to market needs (Manners-Bell and Lyon 2012).

The concept of constructing products in large complex facilities could become obsolete as companies adopt the more flexible model of additive manufacturing (Cottrill 2011).

3D printing is expected to have a significant impact on domestic and international freight operators, in particular regarding the reduction of the importance of some transport paths, and possibly lead to the opening of new ones. A recent analysis (Tipping, Schmahl, and Duiven 2015) for Strategy& about two dozen industry sectors, found that up to 41 percent of the air cargo business and 37 per cent of businesses container ocean carriers is at risk because of 3D printing.

Ye et al., (2015) based on a model, conclude that, in the next two decades, 3D printing is not likely to pose a threat, on the concept of significant production capacity, or reduce the transport flow, in terms of global container traffic. As the GDP of the world's population is not likely to decline over the next 50 years, world trade will probably continue to cause high demand for transport.

MARITIME INDUSTRY CHARACTERISTICS

As AM is starting to consolidate in industry, can offer lessons guiding changes. It is understood that any lessons learned, before applied should take into account the specific characteristics of the maritime industry. Some of the characteristics are similar to industries with moving assets, such as aerospace and defense, but there are some that are met only in maritime. In this section we will briefly refer to features different from a unit permanently installed in one place and therefore have a permanent supply network. For a more detail refer to Eruguz, Tan, and van Houtum (2015).

Although resistance to change is an expected situation, maritime is characterized as conservative to changes, so special attention needs to be paid.

Maritime assets are capital intensive and downtime has financial consequences. Usually operate away from the base in remote areas and are in constant movement. Other sectors with similar characteristics are aircraft / aerospace, defense units, rail and road transport. Ships are usually operating under random environments in isolation from repair facilities and spare parts storage.

Maintenance networks are involving many actors, such as the owners of the assets, systems integrators, original equipment manufacturers (OEM), the service providers and their logistics service providers. The International Maritime Organization and classification societies impose rules that the ships have to follow (such as periodic inspections, mandatory equipment).

The spare parts inventory planning and supply chain include decisions such as determining the appropriate spare parts procurement policies, quantification and distribution of stocks of spare parts and design of service networks, taking into account, for example, emergency transport, side transshipments and joint spare pool Eruguz et al., (2015).

The repair can be executed and stocks of spare parts can be stored on the ship itself, ashore by asset owners, system integrators, service providers, or makers. Assets can be classified as long-lived, since they have a useful life of about 25 years.

The vessel is in an isolated environment. Maintenance and repair works are made by the same crew that operates and lives in it. Information system is long applied among other purposes, for facilitating maintenance and procurements, including spare parts. There are workshops on board, at least at the larger ships, where some fitting works can take place. Vessels (as well as land office) are staffed by technicians, who have to solve whatever problems of the mechanical equipment appear, sometimes working in harsh conditions. The environment is highly corrosive, with turbulence and vibrations. The seating on the ship is subject to vibration, and new techniques must be applied. As the technology matures solutions are found, such as stabilizing devices, to overcome drawbacks as the aforementioned.

Table 1 - Maritime industry characteristics

Strengths	*Weakness*
Maintenance and repair works are made by the same crew that operates and lives in it. Workshop on board. Vessels (as well as land office) are staffed by technicians	The vessel is in an isolated environment
As the technology matures solutions are found	The environment is highly corrosive, with turbulence and vibrations.
Information systems have been long applied.	Conservative to changes.
	The repair can be executed and stocks of spare parts can be stored by many actors.

Table 1 summarizes the more important points that one must have in mind when is thinking in introducing AM in maritime, adopted from (Evanthia Kostidi and Nikitakos 2019).

THE SPARE PARTS SUPPLY CHAIN IN THE MARITIME INDUSTRY

The need for a replacement may occur either because the predetermined stock has fallen below the threshold, or before a predetermined maintenance or because of an extraordinary damage. If the replacement is not in stock at the ship, then a request is sent to the land office (usually by the chief engineer). In the land office, after approval from the technical department, the request passes it to the procurement department.

The purchasing process is pretty much typical (Purchase Order, Request Quotations, Receive Quotations, Select the supplier, Order, Receive order, Invoice). By the time the spare finds its way to the vessel, that in the majority of the cases, has changed position (characteristic of ship). The delivery (except of extreme cases) takes place at a port, or near it.

PORTS AS ADDITIVE MANUFACTURING HUBS

It is common knowledge that ship relay for certain maintenance works while at port. Also, they receive the needed spare parts at / or near the port. That is why there are many workshops and spare part warehouses near the ports. One of the benefits of AM is to produce the part by the end user at the place it is needed, the time it is needed, avoiding the part inventory. Obviously, the best place is onboard. But there are some obstacles to that choice. One obstacle is the vessel environment (constant vibrations). So, the next best place it is near the port.

What one would need is the proper machine, a file with the information to instruct the machine, and the raw material. With the push of a button the machine will start to make the part. The decisions that must be made are: 1) are the needed (machine, file, and raw material) available? 2) Is it more economic to make than buying the part?

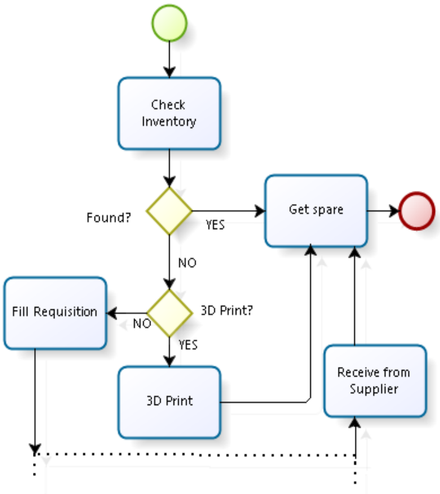

Figure 1: 3D printing decision (Kostidi and Nikitakos 2018)

Adopting AM, making new spare parts for the vessels arriving at the port, is not the only contribution of this technology. Employing AM in maintenance, broken or wired parts can have a second, third, etc. life, reducing waste. Re-cycling can be done locally or even in situ, reducing transport and logistics. Plastics can be re-melted at home and directly used again in a 3D printer contributing to the circular economy.

BENEFITS OF AM TO THE SPARE PARTS SUPPLY CHAIN

Mashhadi, Esmaeilian, and Behdad (2015) traced the transformative effects of additive manufacturing on traditional supply chains, using simulation tools. Their results show the possibility of lead time reduction in AM based supply chain. In addition, System Dynamics illustrated the potential for less ‘pipeline’ effect in AM compared to traditional supply chain.

Digitalized and localized supply chains enable the minimization of delivery lead-times in remote locations and harsh environments has a significant potential to mitigate most spare parts related challenges present in the offshore petroleum industry (Ratnayake 2016).

Khajavi, Partanen, and Holmström (2014) through scenario modeling of a real-life centralized and decentralized applications of AM on the configuration of spare parts supply chains in the aeronautics industry compared operating cost, including downtime cost, with a conventional production. They conclude that production led to a reduction in inventory costs and spare parts transportation costs. They also note that using current AM technology, centralized production is clearly the preferable supply chain configuration in the case example. However, distributed spare parts production becomes practical as AM machines become less capital intensive, more autonomous and offer shorter production cycles.

By simulation Li et al. (2017) showed that the AM-based supply chains are indeed superior to the conventional one in terms of total variable costs. With regard to the carbon emissions, AM is usually considered as a green manufacturing technology. According to this study’s simulation results, the total carbon emissions of the spare parts supply chain adopting AM are indeed lower. The dominant source of the carbon emissions is related to raw materials used for AM manufacturing. Thus, AM can be a method to control the carbon emission of a spare parts supply chain by shortening its channel length.

In a more recent work H. Khajavi, Holmström, and Partanen (2018) quantitatively examined the feasibility of different AM-enabled spare parts supply chain configurations, sing cost data extracted from a case study. They suggest that hub production configuration depending on the utilized AM machines can provide economic efficiency and effectiveness to reduce equipment downtime.

Holmström et al. (2010) describe and evaluate the potential approaches to introduce rapid manufacturing (RM) in the spare parts supply chain for the aircraft industry. Their position is that on demand RM is an increasingly feasible and attractive alternative for spare parts that are not well-suited for mass-production, and where the cost of inventory obsolescence is high. Considering the trade-offs involved, on demand and centralized production of spare parts is proposed as the most likely approach to succeed. They also suggest that, if RM technology develops into a general-purpose technology the distributed approach becomes more feasible.

For the same industry, Liu et al. (2014) performed sensitivity analysis to evaluate the impact of AM in the aircraft spare parts supply chain based on the well-known supply chain operation reference model. A case study was conducted based on data obtained in the literature. Their result shows that the use of AM will bring various opportunities for reducing the required safety inventory of aircraft spare parts in the supply chain.

Muir and Haddud (2018) approximate the impact that additive manufacturing (AM) will have on firm inventory performance (IP) and customer satisfaction (CS) when it is applied within the spare parts (SP) supply chain of manufacturing organizations, using online survey was to collect primary data. Their results revealed that AM was considered a suitable vehicle for the fulfillment of SP demand. However, AM appeared to make no material difference to CS; the scenario used improved delivery time of SP but increased price. Also, AM was thought to improve inventory performance IP through less reliance on buffer stock to manage supply risk (SR) and spikes in demand and less carrying of SP at risk of obsolescence.

The impact of additive manufacturing (AM) implementation on aircraft supply chain (SC) networks was also assessed by Ghadge et al. (2018). Additive and conventional manufacturing spare part inventory control systems are studied and compared, revealing insights into SC performance. A significant improvement in SC efficiency is observed through the implementation of AM, rendering it a worthwhile investment for global SCs. AM helps to balance inventory levels and increase responsiveness while decreasing disruptions and carbon emissions in the supply networks.

Westerweel et al. (2018) investigate the potential of on-site printing spare parts at remote geographic locations, considering a periodic-review spare parts inventory control system with two supply sources, one of them is printing, and the other is the traditional. Their results indicate that on-site general-purpose additive manufacturing (AM) technology, as a temporary solution to shortages, leads to large operational cost savings through on-site inventory reductions and increased asset availability.

Table 2 - Benefits of AM in the SPSC (adopted from Kostidi and Nikitakos, 2019)

Benefit	*Author(s)*
Lead time reduction, less 'pipeline' effect	Mashhadi, et. al (2015)
Distributed production led to a reduction in inventory costs and spare parts transportation costs.	Khajavi et al. (2014)
Superior to the conventional one in terms of total variable costs. Carbon emissions of the spare parts supply chain adopting AM are indeed lower.	Li, et al. (2017)
Hub production can provide economic efficiency and effectiveness to reduce equipment downtime.	Khajavi et al. (2018)
Feasible and attractive alternative for spare parts that are not well-suited for mass-production	Holmström et.al.(2010)
Opportunities for reducing the required safety inventory	Liu, et.al, (2014)
Fulfillment of SP demand	Muir, and Haddud, (2018)

AM helps to balance inventory levels, and increase responsiveness	Ghadge, et.al. (2018)
As a temporary solution to shortages, leads to operational cost savings through on-site inventory reductions and increased asset availability.	Westerweel, et al. (2018)

Most of the work presented in this section is from the aerospace. Regardless the research method some conclusions can be drawn on the benefits that AM could bring in the SPSC. Fabricating parts downstream the chain, in distributed localized hubs can level fluctuating and sporadic demand, not only as a temporary solution to shortages. Lead times are reduced, increasing responsiveness to customer and providing effectiveness to reduce equipment downtime. AM offers opportunities for reducing the required safety inventory and hence led to a reduction in inventory costs and spare parts transportation costs. AM can be a method to control the carbon emission of a spare parts supply chain by shortening its channel length.

BARRIERS - SUCCESS FACTORS FOR THE DIGITAL TRANSFORMATION

The analysis and discussions of different empirical findings shed light on the success factors and implications of digital transformation, which many organizations face today or are likely to face in the near future. The importance of a supportive and agile organizational culture, well-managed activities, engaged managers and employees, and leveraged external and internal knowledge is emphasized in a review (Osmundsen, Iden, and Bygstad 2018).

Barriers towards the introduction of AM

All technological changes face barriers prior to the implementation and must be treated accordingly. Vogelsang et al. (2019) analyzed barriers towards the digitalization of enterprises in manufacturing in order to understand the barriers which hinder or even stop the digital change in enterprises. The identified barriers were grouped into individual, organizational, environmental and technical barriers as well as a lack of skills.

The common individual barriers are: fear of data loss of control, fear of transparency /acceptance, fear of job loss. Organizational and cultural barriers are: keeping traditional roles/principles, no clear vision/ strategy, resistance to cultural change / mistake culture, risk aversion, lack of financial resources, lack of time (Ballardini, Flores Ituarte, and Pei 2018).

Among the technical barriers need to be overcome are low number of usable materials, insufficient accuracy levels, tolerances, and the limited build chamber volumes were perceived as the major technical barriers (Kretzschmar et al. 2018). Another barrier is that design is for traditional manufacturing, and does not take into account the capabilities of AM.

CAD files often do not exist and technical drawings can be difficult to locate (Ballardini et al., 2018). Barriers such as standardization, quality assurance, intellectual property rights protection, legacy of non-digitalized product and component information, have to be faced.

Overcoming the barriers

For overcoming the individual and organizational barriers the theory and practice of change management may guide the management movements, in dealing with challenges in a corporate or personal environment through permanent and primarily proactive changes in awareness and behavior.

The concern if the spare part made by the AM is comparable with the part made by the traditional method could be overcome by the development of standard methods to test processes and parts (Monzón et al. 2014). Quality assurance could be assured by standardizing the manufacturing process.

Additive manufacturing (AM) techniques have significant barriers to overcome in delivering a manufacturing process that produces consistent quality and safety. Lloyd's Register and TWI (2017)(transformation n.d.) have produced "Guidance Notes for the Certification of Metallic Parts made by Additive Manufacturing" to help manufacturers forge a path to certified AM parts. They are distinguished in 5 key areas including design, materials, manufacturing, manufacturing, inspection and testing. ("Testing the Potential of Additive Manufacturing - DNV GL" n.d.)DNV GL (2017) published classification guideline for the use of additive manufacturing (AM) in the maritime and oil & gas industries. The guideline aims to help manufacturers and sub-suppliers of materials, parts and components, service suppliers and end users adopting AM technologies.

As far as the cost is concerned, as the market advances, patents expire, and demand grows, the machine cost as well as the production cost will fall. Intellectual property rights could be protected by servitazation contracts, or by buying the part accompanied with the file containing the requirements to make the item, or even codification system. Designs have to be redesigned and optimized, taking into account the requirements and the capabilities of AM. Education and skills, of the designers and the new machine operators, have to be adapted to the requirements of the new technology.

Table 3 - Overcoming the barriers (adopted from ***(Evanthia Kostidi and Nikitakos 2019)***

Barriers	**Overcoming the barriers**
Common individual and organizational barriers	The well-known theory and practice of change management
Quality assurance	Standardization of the manufacturing process
Cost of the machine and process	The machine cost as well as the production cost tend to fall
Intellectual property rights	Servitazation contracts, or by buying the part accompanied with the rights
Utilization of the capabilities of	Redesign and optimization

AM	
Skills shortage	Education and training adapted to the requirements of the new technology

CONCLUSIONS

The conversion of information into a digital format makes it easier to preserve, access, and share it (digitization), moving industry and manufacturing to data-driven, leading in new business models for product design, manufacturing, distribution and service.

With the digitization of the industry and the recent technological advancements of computing and visualization technologies, the opportunity to access actionable information for maintenance provides additional benefits. Apart from products, packages of customer-focused combinations of goods, services, support, self-service, and knowledge, may be offered.

The published work regarding the observations from the actual implementation of additive manufacturing as it is finding its way into mainstream manufacturing industry reveals its benefits and challenges.

Additive manufacturing is a different manufacturing methodology, that can produce functionally integrated components (including spare parts) in a single production step, in small batches, eliminating stages of the traditional production, shortening the supply chain. The main benefit of this technology is that it allows the flexible production of customized products at no extra cost in terms of manufacturing. Even though the reviewed research came mostly from the aerospace and the defense industry, some conclusions can be drawn on the benefits that AM could bring in the SPSC. Fabricating parts downstream the chain (at the port for instance that is near the end of the SPSC), in distributed localized hubs (such as warehouses and local labs at the ports) can level fluctuating and sporadic demand. Lead times are reduced, increasing responsiveness to customer and providing effectiveness to reduce equipment downtime. AM offers opportunities for reducing the required safety inventory and hence led to a reduction in inventory costs and spare parts transportation costs. AM can be a method to control the carbon emission of a spare parts supply chain by shortening its channel length, and also contributing to the circular economy.

The purpose of this article was to highlight that there is potential for the introduction of additive manufacturing in the configuration of spare parts supply chains in the maritime industry, by referring mostly in published work form aerospace and defense, since there are similarities.

Any lessons learned from other industries, before applied should take into account the specific characteristics of the maritime industry. To mention a few characteristics: the vessel is in an isolated environment, the environment is highly corrosive, with turbulence and vibrations, vessels (as well as land office) are staffed by technicians, information systems have been long applied. Since maritime industry has specific characteristics, research must be done, taking into account these characteristics, studying the benefits and barriers from the introduction of AM into the maritime spare part supply chain.

As all technological changes, the implementation of AM will face barriers, individual, organizational, environmental and technical barriers as well as a lack of skills, that must be treated accordingly, before they hinder or even stop the digital change in the enterprises.

In our future research we are planning to examine issues like: inventory costs savings when additive manufacturing is introduced in the SPSC, and changes concerning warehouse locations to better serve the maritime industry.

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